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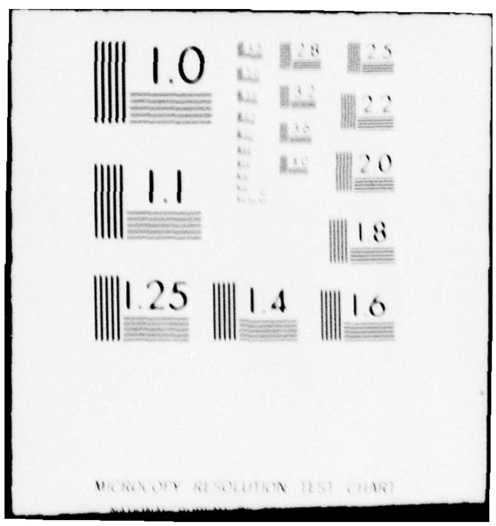
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NOSC







Technical Report 237

# REMOTELY MANNED UNDERSEA WORK SYSTEMS AT NAVAL OCEAN SYSTEMS CENTER (NOSC)

HR Talkington

15 April 1978

Status Report



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NAVAL OCEAN SYSTEMS CENTER
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AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

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## ADMINISTRATIVE INFORMATION

The information presented in this report was compiled and written under task number 63713N DOT 12626. The tasks and equipment described within are projects of the Ocean Technology Department.

Released by
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The Remotely Manned Undersea Work Systems developed at the Naval Ocean Systems Center (NOSC) are herein described. This paper begins with a description and analysis of typical underwater work tasks. Based on the function derived from the tasks analysis, various underwater transporters (vehicles or divers systems) will be described; the sensors required to locate and provide support at the work site will be discussed. Based on the various components required to perform underwater tasks thus delineated, systems synthesis is applied to provide the most efficient operations by best combining the complementary characteristics of each of the subsystems. (cont'd)

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The tasks defined and equipment described are applicable to most undersea operations such as survey, inspection, search, salvage, recovery of items from the seafloor, emergency rescue of submersibles or habitats, as well as performance of dexterous tasks on undersea installations.

# SUMMARY

The Remotely Manned Undersea Work Systems developed at the Naval Ocean Systems Center (NOSC) are herein described. This paper begins with a description and analysis of typical underwater work tasks. Based on the function derived from the tasks analysis, various underwater transporters (vehicles or divers systems) will be described; the sensors required to locate and provide support at the work site will be discussed. Based on the various components required to perform underwater tasks thus delineated, systems synthesis is applied to provide the most efficient operations by best combining the complementary characteristics of each of the subsystems.

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## CONTENTS

## INTRODUCTION

Any discussion on the research and development of work systems must begin with an understanding of the tasks to be accomplished. The ultimate objective of the systems and components discussed in this paper is to perform useful work in the sea. Therefore, knowledge of both the undersea environment and the required tasks is paramount in planning and conducting a research and development program for underwater work systems.

## TASKS

The tasks that most strongly affect the development of underwater systems are as follows:

SEARCH - to find lost items, locate work sites, and survey seafloor areas

INSPECTION - to classify detected targets, monitor continuing operations, define the integrity of structural components or pipelines, detect leakage of pollutants, and record the condition of objects, e.g., ships, aircraft, and canned waste, on the seafloor

RECOVERY - to attach lifting devices, cut away moorings or clutter, and provide vertical and horizontal lifting forces to effect transport of objects from the seafloor to the surface

ASSEMBLY, MODIFICATION, OR REPAIR - to conduct work on objects on the seafloor or within the volume, assemble parts, and effect repairs, improvements, or alterations

NEUTRALIZATION - to modify objects (possibly by explosive means) to render the site safe for future operations, e.g., mine clearance or removal of obstructing wreckage.

## VEHICLES

To perform undersea tasks, service platforms must provide mobility and motive power for the working tools and support to the sensors needed for acquisition and monitoring of the work site. These service platforms may range from a human diver, for minor shallow water work, through a range of tethered and untethered, manned and unmanned submersible systems. Both diver and manned systems are covered most adequately elsewhere; therefore, this paper will concentrate on the application of remotely controlled unmanned systems, with special emphasis on the required sensors and tools.

Although these systems are referred to as unmanned, this does not mean that man has been removed from the system; it simply implies that the human operator is not aboard the vehicle at the work site. The human operator (figure 1) is totally integrated into the system and has full perception because of displays from the sensors aboard the vehicle and the controls for its operation. Thus, these vehicles would be more properly termed "remotely manned undersea vehicles."

At the Naval Ocean Systems Center (NOSC), a broad family of undersea submersible systems has been developed. The following are examples of tethered unmanned vehicles of various sizes and capabilities to match varying requirements.

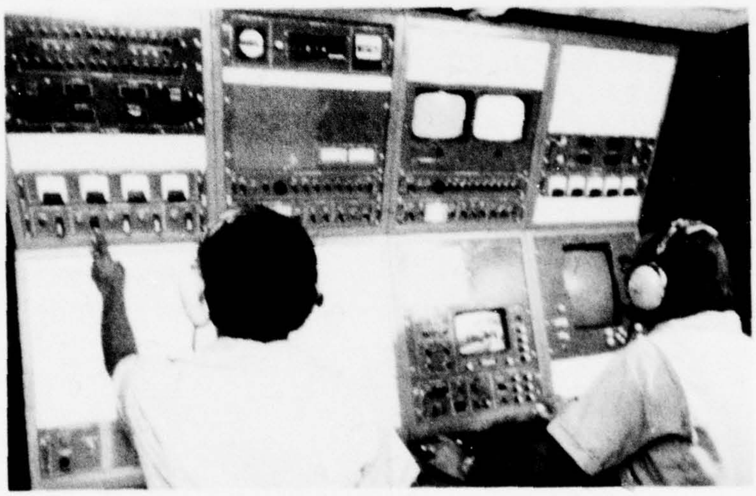

Figure 1. Operators at RUWS control console.

## CABLE-CONTROLLED UNDERWATER RECOVERY VEHICLE (CURV II)

CURV II is an unmanned tethered submersible capable of operating to 2500 feet (762 meters). It is the successor to CURV I which recovered the H-bomb off the coast of Spain in 1966. The configuration of CURV II (figure 2) is typical of most unmanned vehicles; it has an open rectangular framework to support the sensors and tools, two horizontal propulsion motors to drive and steer the vehicle, one vertical motor for close vertical control, and buoyancy of approximately 25 pounds (11 kilograms). The vehicle is 6.5 by 6.5 by 15 feet long (2 by 2 by 5 meters), weighs 3000 pounds (1361 kilograms) in air, and operates at submerged speeds to 3 knots (1.5 meters per second) and to depths of 2500 feet (762 meters). The sensors include a Straza 500 active-passive sonar, acoustic altimeter, depthometer, compass, twy Hydro Products television cameras with lights, and an EG&G 35mm still camera with strobe. One major feature of all surface-powered vehicles is that their bottom time is only restricted by the time or ability of the surface-support craft to stay on station.

The CURV II system consists of the vehicle, control cable, and control console. Although it normally operates from the YFNX-30 surface-support ship, the system can be air transported to operate from any surface ship of opportunity. It is primarily used for recovery of practice torpedoes from NOSC ranges.

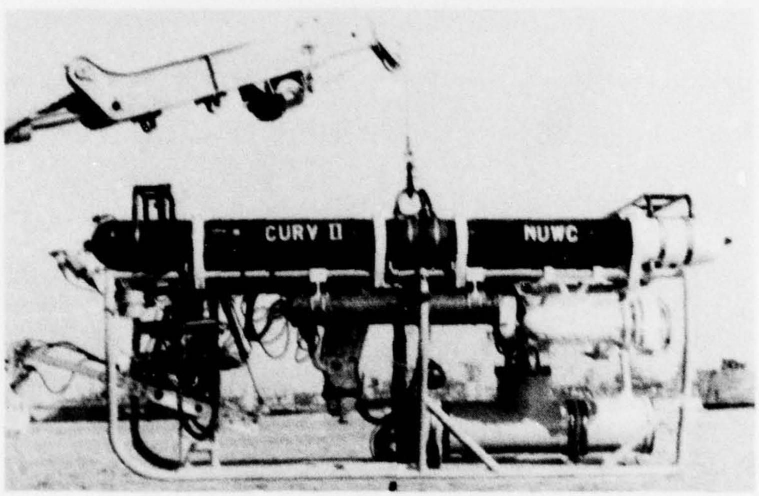


Figure 2. CURV II.

## CABLE-CONTROLLED UNDERWATER RECOVERY VEHICLE (CURV III)

CURV III (figure 3), a more modern and deeper depth version of the CURV II, is capable of operating in water depths of 7000 feet (2134 meters). The CURV III system is comprised of the vehicle, control cable, and control console. Although it normally operates from the YFNX-30, the system is designed so that all major operational components can be disassembled, air transported to a work site, and installed on any surface craft that has adequate deck space. The vehicle normally carries a hydraulically-operated claw for attaching and recovering items such as ordnance, from the ocean floor. For special tasks, the claw is removed and replaced by a variety of grasping, cutting, or working tools. The vehicle also contains the necessary equipment for searching, locating, and documenting the lost item. Control of the vehicle and monitoring of the operations are done in the control van. The vehicle is 6.5 by 6.5 by 15 feet long (2 by 2 by 5 meters), and weighs 4500 pounds (2040 kilograms) in air. It normally operates to depths of 7000 feet (2134 meters), but can be modified for emergency operations to 10,000 feet (3050 meters). Its instrument suite includes a Straza 500 active-passive sonar with transponder integration capability, acoustic altimeter and depthometer, compass, two Hydro Products television cameras with lights, and an EG&G 35mm still camera with strobe.

CURV III is a versatile underwater vehicle that can be readily modified to accommodate a wide variety of underwater tasks. It has demonstrated its search and recovery capabilities on the west coast as well as in the Atlantic Ocean, most notably during the 1973 rescue of the PISCES III submersible off Ireland.

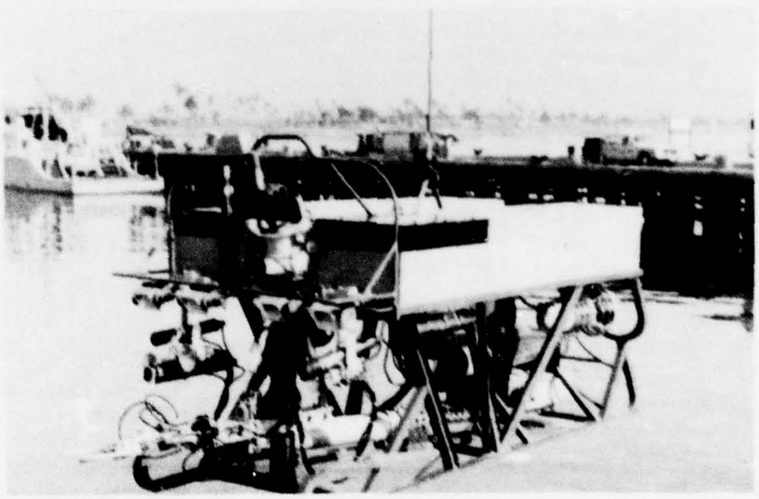

Figure 3. CURV III.

## REMOTE UNMANNED WORK SYSTEM (RUWS)

Under the Deep Ocean Technology (DOT) program, NOSC is developing RUWS, a remotely-controlled submersible system that can perform a variety of work tasks at ocean depths to 20,000 feet (6000 meters). This depth capability provides access to more than 98 percent of the ocean floor. The system is designed for air transport and deployment from specified ships of opportunity.

RUWS equipment on the support ship consists of a control center, motion compensation deck-handling system (MCDHS), diesel-power generators, and maintenance van. A single-coaxial-core, high strength, synthetic cable connects the control center and the primary cable termination (PCT). The PCT serves as a line weight to aid on-stationkeeping and to limit forces that might otherwise be transmitted to the work vehicle. It is the power and signal distribution center between the primary cable and the flexible, multiconductor, vehicle tether. With its own propulsion system, it also provides the capability for ship-coordinated transit across the ocean floor to establish a new holding position.

The RUWS work vehicle (figure 4), which weighs 4300 pounds (1950 kilograms) in air, is 4.5 by 4.5 by 11 feet long (1.4 by 1.4 by 3.4 meters). The work vehicle moves freely at the end of a buoyant flexible tether deployed from the PCT. Vehicle sensors include an active-passive CTFM sonar, bottom transponder integrator, altimeter, depthometer, compass, head-coupled stereo television with lights, and EG&G 35mm still camera with strobes. All signals and power needed to control and operate the submersible are multiplexed on the single coaxial core of the primary cable. A highly accurate, deep-ocean navigation system provides coordinated inputs to the vehicle's operators and the support ship's bridge.

The deep-ocean navigation system and a local-area, bottom-search sonar are used by the operator to guide the vehicle work site. At the work site a 4-degree-of-freedom grabber holds the workpiece, while a highly dexterous, 7-degree-of-freedom manipulator positions individually powered tools or performs other work functions.

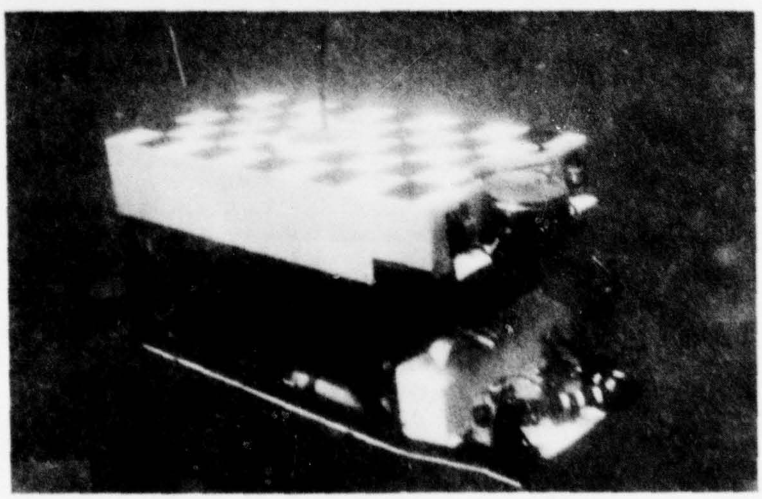

Figure 4. RUWS.

**SNOOPY**

SNOOPY is the smallest in a series of lightweight, portable, unmanned, undersea vehicle systems. Built as an experimental vehicle, it is capable of carrying a television camera with a 100-watt, mercury vapor light source into the sea environment. As such, it can replace a diver for many tasks in which observation or surveillance is required. SNOOPY (figure 5) has two unique features:

(1) all propulsion power is sent from the surface by hydraulic lines and

(2) an automatic depth-keeping capability is provided by a variable buoyancy chamber and a depth feedback system.

A small, electrically-powered grabber is mounted on the forward end for implanting or retrieving lightweight objects. The vehicle is approximately 1 by 2 by 3 feet long (0.3 by 0.6 by 0.9 meters), weighs 50 pounds (23 kilograms) in air, and operates at speeds to 2 knots (1 meter per second) to depths of 100 feet (30 meters).

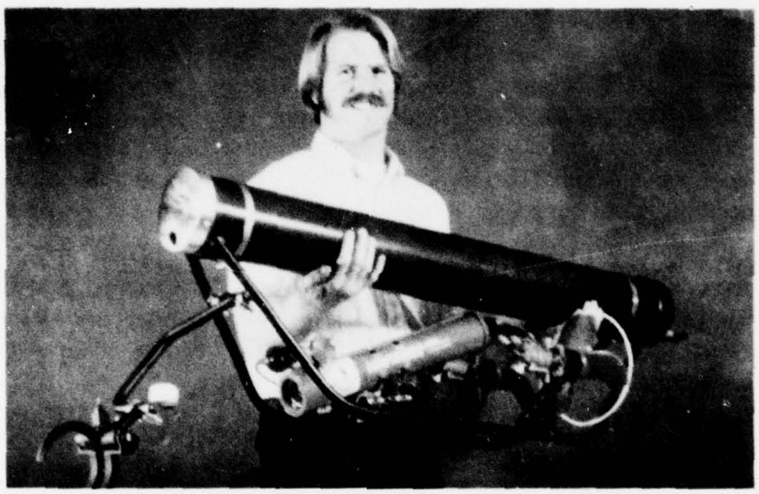

Figure 5. SNOOPY.

## ELECTRIC SNOOPY

ELECTRIC SNOOPY, the successor of SNOOPY, principally differs from its predecessor in its propulsion scheme. This experimental vehicle (figure 6) uses three ¼-horsepower, oil-filled, pressure-balanced electric motors for thrust in the horizontal and vertical directions. This approach allows the use of a small-diameter ¼ inch (0.6 centimeter), 1500-foot (457 meters), coaxial-tether cable. AC power, along with multiplexed control signals, is sent down the cable and converted to variable, DC-motor-driven voltage through motor controllers. A single joystick controls forward, reverse, and turning motions. Twin pressure hulls house all vehicle electronics, a television camera, and a super-8 movie camera, all of which provide a streamlined and responsive vehicle. The super-8 camera provides intervals of action footage or a large number of individual-frame photographs. A single light illuminates both the television and film cameras. The 1.5- by 2.0- by 3.0-foot-long (0.5 by 0.6 by 0.9 meters) vehicle weighs 150 pounds (68 kilograms) in air and operates to depths of 1500 feet (460 meters).

When used in conjunction with a small buoyant reel, ELECTRIC SNOOPY has demonstrated that it can be used to attach a light line to a seafloor object, such as a stricken manned submersible, so that a heavy lift line with a "go-getter" can be guided to a hard point for surface lift.

Figure 6. Electric SNOOPY.

## NAVFAC SNOOPY

NAVFAC SNOOPY is a small, remotely-controlled vehicle system that was designed and built for the Naval Facilities Engineering Command to support ocean construction work. Its primary uses are optical surveys of proposed undersea construction or implantment sites, surveillance and documentation of diver operations, and general undersea inspection and documentation. The 2- by 2-by 4-foot-long (0.6 by 0.6 by 1.2 meters) vehicle (figure 7) weighs 300 pounds (136 kilograms) in air and operates to 1500 feet (460 meters). It utilizes four hydraulically-powered thrusters for horizontal and vertical excursions. The three horizontal thrusters are controlled by a three-axis, proportional joystick for integrated forward, reverse, turning, and lateral vehicle motions. The vertical thruster's control uses automatic depth- and altitude-holding circuitry with manual override. A low-light-level television camera with a 250-watt, quartz iodized light is used for viewing, and a super-8 movie camera provides color documentation. Other sensors include a compass, altimeter, depthometer, and Straza 250 passive-active CTFM sonar. The vehicle's power, control signals, video signal, and instrument data are multiplexed onto a single coaxial tether.

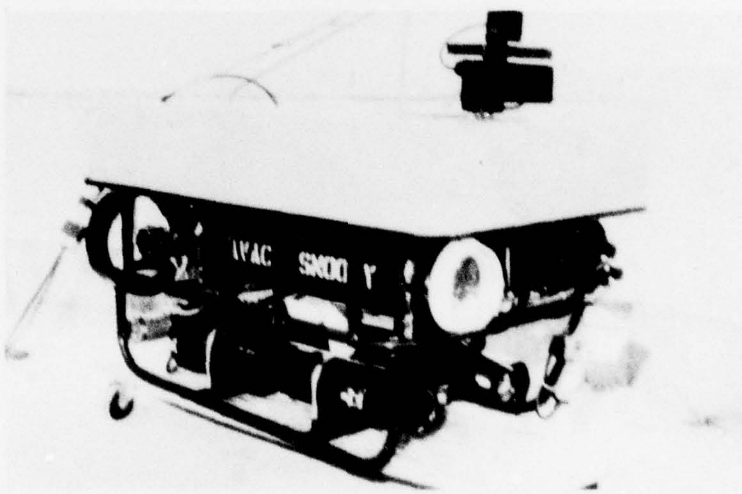

Figure 7. NAVFAC SNOOPY.

## SENSORS

The vehicles already described are primarily outfitted with commercially available sensor systems, e.g., high resolution sonars, television and film cameras, compasses, and depth-and height-sensing devices. Special sensor development in the fields of high resolution acoustic imaging, real-time optical mapping, and minimal-sized sonar and the application of pressure-tolerant-electronic (PTE) components to all possible systems are the subjects of current research and development programs. In addition, the output from material's research and development directly applies to the structural components, windows, and cabling systems of undersea work systems.

### ACOUSTIC IMAGING SYSTEM (AIS)

The acoustic imaging program was initiated as part of the Navy's DOT program to improve the range of underwater visibility, particularly in turbid water. The general objective is to develop and demonstrate acoustic imaging technology for underwater search, recovery, classification, manipulation, and inspection aboard manned and unmanned submersibles to depths of 12,000 feet (3660 meters). The program has focused on the development of a holographic (lensless) system. The AIS was designed to achieve a recognizable image of a beer can in turbid water at ranges to 25 feet (8 meters) anywhere within the 11- by 11-degree (0.2 radian) field of view. Larger objects can be seen at ranges up to 150 feet (46 meters). Photographs are taken at the rate of one every 2 seconds with a future capability of 15 per second. The system consists of two assemblies: (1) an underwater unit (figure 8) which has an acoustic projector, receiving hydrophone array, and processing electronics, and (2) a rack of control electronics that holds the control panels, minicomputer image reconstructor, and displays.

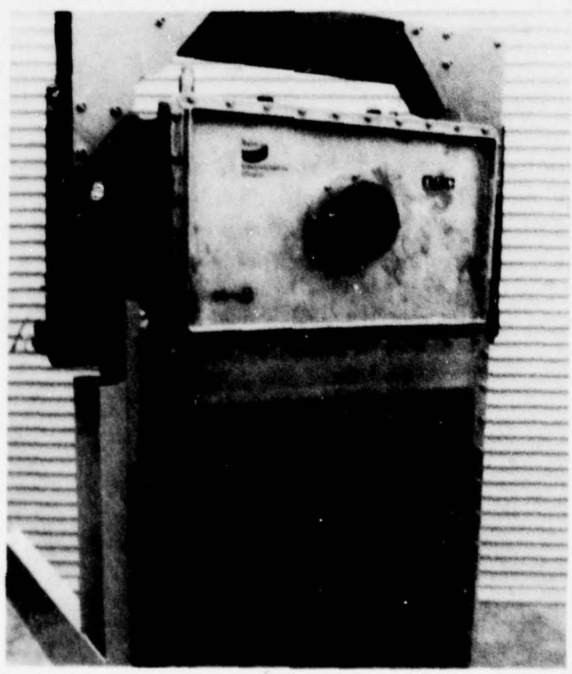

Figure 8. Transmitter/receiver unit for acoustic imaging system.

The acoustic projector sends high frequency (642 kilohertz) sound into the water. Objects reflect the sound waves in patterns that are dependent on their shape. The acoustic detector (48 by 96 elements in a 2-foot [0.6 meter] square) senses, processes, and stores the sound pattern as an acoustic hologram, which is then digitized and transferred to the holographic reconstructor, a digital minicomputer. The minicomputer processes the hologram to form an image which is then displayed on a screen. All electronics inside the underwater housing are pressure tolerant, that is, the housing does not withstand the ambient pressure, but transmits it directly to the electronic components themselves within the oil-filled, pressure-compensated container.

The acoustic imaging system is envisioned as being very useful in two scenarios. As a classification system in conjunction with a search sonar, it will provide target identification, as would a television, but with greater range and less sensitivity to water turbidity. As a visual system, it provides visibility for the operation of underwater work systems, even when there is turbidity caused by the mud turned up by the work system.

## REAL-TIME OPTICAL MAPPING SYSTEM (ROMS)

The concept behind the development of ROMS was to combine the qualities of (1) high optical resolution, (2) a large swath width, and (3) a real-time readout to produce a real-time optical picture of the ocean bottom for fast seafloor search and mapping. It thus bridges the gap between existing acoustic systems, which offer long range and real-time operation but are limited by low resolution; and photographic systems, which offer high resolution but are not capable of real-time operation.

ROM's capabilities depend upon a set of rotating, three-faceted mirrors mounted on a single shaft (figure 9). The first mirror sweeps an argon laser beam across a 120-degree (2.09 radians) angle. The second, synchronized with the first, receives a portion of the beam returned from the seafloor and reflects it through a focusing system to a photomultiplier. The photomultiplier signal is preamplified and processed before it is transmitted to the surface, where it is further processed to make it compatible with a cathode-ray-tube (CRT) display. The CRT display is arranged to provide a "waterfall," two-dimensional, map-type display, and the data are permanently recorded on hard copy for postrun analysis. The operator can control the display and adjust its contrast or zoom-in on an object of interest. The receiving mirror is mounted in a water-filled, acrylic housing to minimize light losses at the water-window-air interface. Its field of view is restricted to a region near the seafloor to minimize first-order backscatter. Backscatter is sufficiently reduced to make the system power limited.

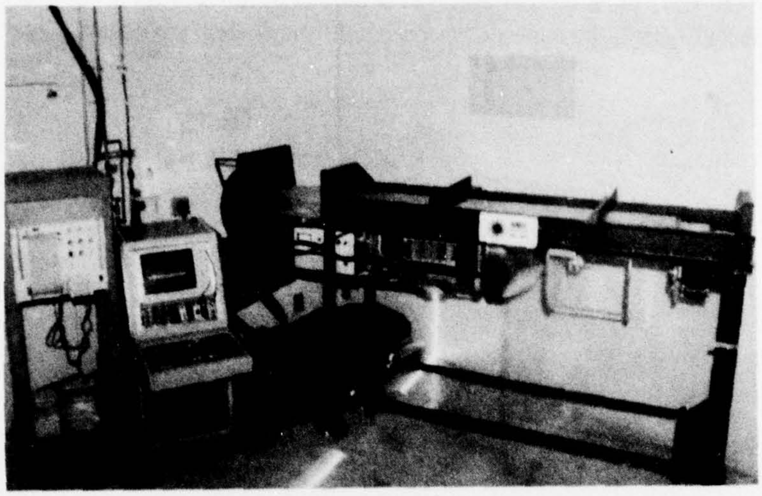

Figure 9. Lab test of the real-time optical mapping system.

The demonstration hardware provides a swath width of 400 feet (122 meters) when operated at an altitude 120 feet (37 meters) above the seafloor, with a resolution element size of 3 inches (8 centimeters). Higher resolutions, but smaller swath widths, are obtained by lowering the operating altitude. A 5-knot (2.6 meters per second) speed of advance provides a search rate of 0.2 square nautical mile per hour.

## MINISONAR

To provide an acoustic navigation capability for very small vehicles, a sonar device of minimal size is required. The goal of a current development effort at NOSC is an electronics "scan-within-pulse" sonar with an underwater head not larger than 3 by 6 by 6 inches (8 by 15 by 15 centimeters) that will have a range of 100 to 300 feet (30 to 90 meters) and a resolution of 3 inches (8 centimeters). The prototype demonstration model is currently under test.

## PRESSURE TOLERANT ELECTRONICS (PTE)

With the advent of solid-state electronic components, a major improvement in the packaging of undersea electronic systems is possible. The primary characteristic of PTE, i.e., the electronics are not protected from the pressure, describes its real advantages. It frees the designer from constraints imposed by pressure vessels, and it provides almost unlimited freedom in the choice of container size, shape, and materials. Since there is no pressure difference between the inside and outside of the container, there is no need for heavy containers or high-pressure penetrators and seals. At the present time, all known PTE systems use liquid-filled, pressure-equalized containers. In addition to offering the advantages of few container constraints, such systems can or will be able to allow control of package buoyancy, eliminate the potential for catastrophic pressure seal and penetrator failures, provide a low thermal resistance path to the ocean, and permit the design of flexible, inexpensive electronic systems capable of operation at any depth. There are currently a large number of electronic devices and components that have been tested and found adequate for PTE application. Many amplifiers, signal processing devices, and sonar

subcomponents have been built. Figure 10 shows a complete television camera modified with selected PTE parts; the camera can be taken to any depth without a heavy pressure case.

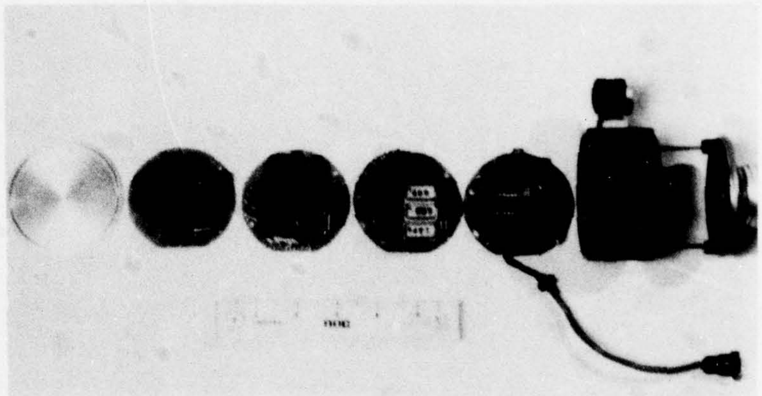

Figure 10. Pressure tolerant electronic television.

## MATERIALS

There is a constant search for better materials for use in the undersea environment. To support undersea work systems, three problem areas are receiving special attention at NOSC: transparent materials, high strength-to-weight ratio materials, and undersea cabling. The transparent materials program includes continuing development of design and certification criteria for the use of acrylics, glass, and ceramics in windows (figure 11),

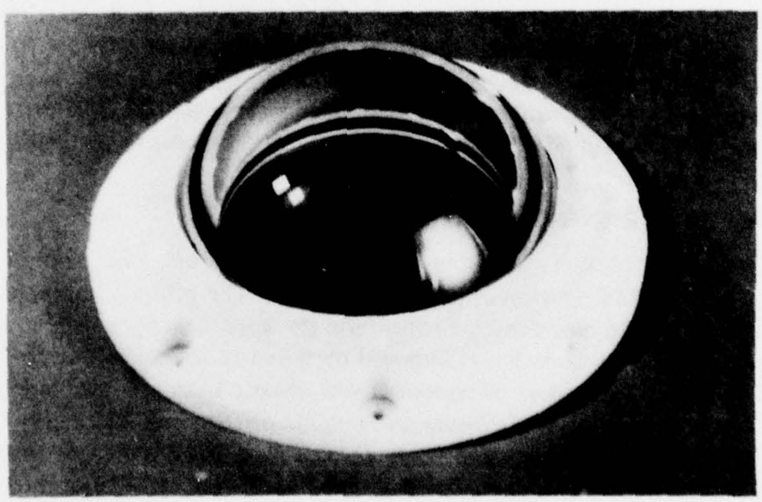

Figure 11. Deep ocean window.

pressure hulls, and structural components for increasing depth and stringent operating conditions. The aramid fiber kevlar is being applied as a strength member for undersea cabling and as the reinforcing member in plastic composite sheets and structural members. The resulting weight savings is a factor of four to six. To lighten the density of undersea cables, increase the data signal bandwidth and reduce cross-talk and outside electrical and radio-frequency interference; fiber-optic elements are also being applied to the tether cables of undersea vehicles.

## TOOLS

For most routine undersea operations, two-function claws of various sizes and shapes, cutters, and simple toggle bolts are sufficient for most work tasks. For certain of the more dexterous tasks, multifunction manipulators and specialized tools are necessary.

### MANIPULATORS

A manipulator must be mechanically well designed for performing the required tasks in the marine environment, and it must be integrated with controls and displays so that the operator can perform coordinated, accurate motions. Anyone with experience in remote work systems develops opinions on how to design a manipulator to optimize the capabilities of the operator through the man-machine interface, but these opinions must be reconciled with the experience of others, i.e., the human factor researchers and the operators.

The optimum manipulator and control system varies with the task. The capabilities of operators also vary, and their preferences are often a function of their experience with particular types of manipulators, controls, displays, and tasks. However, experience has led to a general awareness of certain tradeoffs. For example: for tasks requiring precise positioning, rate-control devices are more accurate; whereas for general reaching and grasping, where coordination is more important than precision, master-slave manipulators are much faster. In rate-control manipulators, position feedback is purely visual; whereas for master-slave manipulators, even with computer-generated displays, there is also a natural feeling of position. Two types of master-slave controls have been used: harness and terminus control. A harness control straps onto, or in some way attaches to, the arm of the operator; the terminus control is held only at the hand or terminus. They operate in the same way: the manipulator (slave) is driven to conform to the configuration and position of the control (master). The harness control may be most valuable for use with anthropomorphic manipulators, especially those with a redundant function for elbow position. Terminus control, much more common in hot-cell nuclear work, generally allows more operator freedom and a greater range of motion and does not require an anthropomorphic manipulator.

For manipulators, such as those on the RUWS (figure 12) and work systems package (WSP), it is anticipated that tasks requiring force feedback will occur. Examples are *drilling and tapping operations where* too much force or misdirected force might result in a broken tool. Of course, wherever possible, tool drive, feed, and alignment should be automatic functions of the tool itself and not of the manipulator. Unfortunately, this is not always possible. Another situation in which force-sensing could be important occurs when the manipulator unexpectedly comes in contact with the work task or the vehicle. Another difficulty that the operator encounters is in maintaining a sense of orientation. Orientation and station-point feedback are provided by two methods: fixed camera and monitor or head-coupled television (the latter method should incorporate head-following translation, if possible). Head-coupled television also alleviates the problem of limited field of view, since a sweep of the head allows the operator to encompass visually as much of the remote environment as desired and the spatial relationship of objects not simultaneously visible in the camera's field of view is instinctively retained.

Figure 12. RUWS manipulator.

It must be cautioned that the best general-purpose manipulator for underwater work is not necessarily the most sophisticated or complex. Cost, reliability, maintainability, and the ability of the trained operator to work within limitations must also be weighed in deciding whether to incorporate seemingly desirable features.

## WORK SYSTEMS PACKAGE (WSP)

An example of integration of manipulators and tools is found in the recently completed work systems package (WSP), developed as part of the DOT program.

The WSP (figure 13) is comprised of manipulators and a variety of hydraulic tools that are integrated to accomplish tasks to ocean depths of 20,000 feet (6100 meters). The system can be readily adapted to the manned submersibles—ALVIN, SEACLIFF, and TURTLE—and the robot vehicles—CURV III and RUWS—to extend their work capabilities. In addition, it can be positioned and controlled by divers or operated from a surface-support ship. The system was designed to perform a complete work operation on the seafloor without resurfacing for tool interchange. Potential tasks include recovery, construction, installation, and repair operations. Low-light-level television cameras with quartz-iodide flood lights augment the operator's vision.

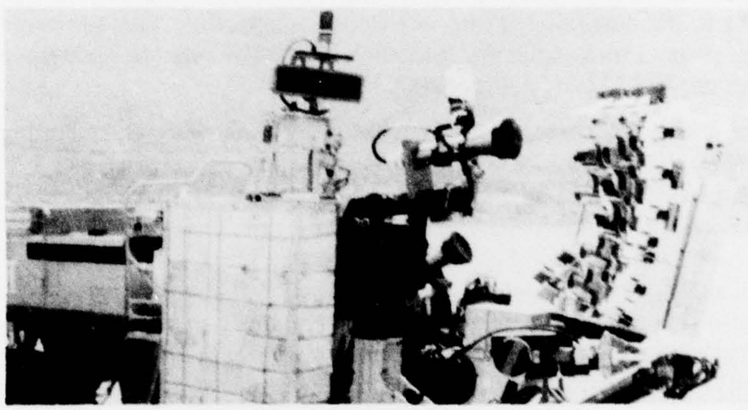

Figure 13. Work systems package.

The skeletal structure of the WSP is a simple tubular network fabricated from 5086-alloy aluminum. Its configuration is the result of spatially arranging all major system components to meet the aforementioned requirements and then connecting them with a single strongback. The problem of use with various submersibles was solved by providing an interface plate between the vehicle and the WSP. The interface plate is mounted to the parent vehicle by a single 1-inch-diameter bolt (2.5 centimeters) that can be severed by either of two explosively-actuated bolt cutters, thereby satisfying the requirement for a single-point jettison capability with redundancy.

It was necessary to reduce the underwater weight of the WSP to make it compatible with the trim capacities of each parent submersible. Blocks of syntactic foam with a density of 35 pounds per cubic foot were shaped and mounted on the package and skid structure. The foam was positioned to avoid interference with work functions while providing good stability characteristics to the host vehicle.

Mounted on each end of the main cross-tube are two simple manipulator or "grabber" arms which can secure and hold a workpiece for stability or assist the dexterous manipulator work arm. They are hydraulically actuated and can perform six rate-controlled functions including a 24-inch (61 centimeters) linear extension. Lift capacity is 250 pounds (113 kilograms) at a 9-foot (3 meters) extension and the grip force is 500 pounds (227 kilograms).

The dexterous work manipulator is a seven-function, hydraulically actuated, rate-controlled arm mounted above and to starboard of center. This position, in relation to the operator's normal viewing position above center and behind the package, is analogous to the relative positions of the right arm and eye of a human; it thus provides some anthropomorphic familiarity to the operator. Lift capacity of the manipulator is 100 pounds (45 kilograms) with the arms fully extended to 6 feet (2 meters). Lines from the main hydraulic power unit run to the jaw. The jaw is equipped with quick disconnects which mate with similar connections on the hydraulic tools. This permits hydraulic power to be coupled underwater and transmitted to the tool when it is grasped, without the need for hoses on each tool.

The tools are held by compliant brushes in a tubular aluminum holder which is positioned opposite the primary manipulator and normally out of the frontal viewing area. The holder can be extended so that the tools are extracted or replaced along a radial line corresponding to the manipulator's linear extension capability, thus shortening the time required to perform a tool exchange. Bits, such as drills or sockets, are held in clips along the upper and outside edge of the holder.

It was envisioned that the WSP would do the work of divers operating at great depths; therefore, large tools are not included. The tools provided are the type and size that would normally be used by a mechanic performing field operations on land. The tool suite was selected on the basis of work functions required to perform typical underwater tasks, such as those encountered in salvage operations. These include debris clearance, hull penetration, lift device attachment, and salvage valve coupling attachment. The tools are divided into three categories: rotary, linear, and power velocity (explosively-actuated). Hydraulic operation was selected for most tools, as well as for the manipulators and other actuators, because of its inherent advantages of precise control, high power density, and insensitivity to depth pressure. The rotary tools, such as the chipping hammer, are powered by small, fixed-displacement piston motors, while the linear tools are operated by linear actuators. Both represent a pioneering effort toward a comprehensive underwater tool suite. The power-velocity tools, cable cutter, and stud driver are used in applications where a high-energy output for a short duration is desired. They are simple and easy to operate, but can be used only once during an operation. Consequently, several spaces in the tool holder are reserved for these tools. Table 1 contains a summary description of WSP tools and their capabilities.

Table 1. Summary of Work Systems Package tool suite.

| Operating Mode | Power Head | Bits | Function | Capability |
|---|---|---|---|---|
| Rotary Hydraulic | High Speed | Wire Brush, grinder cut-off wheel | Brush, grind, cut | 125 in/lb |
| | Low speed | Drill, tap, die | Drill, thread | 275 in/lb |
| | Reciprocating knife | --------- | Rope cut | 2-in rope |
| | Chipping hammer | Chisel | Chip | 37 lb, 21 strokes per second |
| | Impact wrench | Sockets | Bolt, unbolt | 1320 in/lb |
| | Winch | --------- | Pull | 1000 lb |
| Linear Hydraulic | Jack | --------- | Jacking | 19,000 lb, 8½ in |
| | Spreader | --------- | Spreading | 2876 lb, 13 in |
| | Cable cutter | --------- | Cut cable | 23,000 lb, 1-in Wire rope |
| Power Velocity | Cable cutter | --------- | Cut cable | 1¼-in wire rope |
| | Stud gun | Padeye | Attach padeye | 1/8- to 5/8-in thick mild steel |

NOTES: 1 inch/pound = 1.129 848 E-01 Newton/meter
1 inch = 2.540 000 E-02 meters
1 pound = 4.535 924 E-01 kilograms

## SURFACE SUPPORT

No discussion of undersea work systems can be complete without mention of the surface-support craft and handling systems. Although this subject is extensive enough to be a paper by itself, it is sufficient to state that a stable platform with good position keeping is vital to undersea vehicle operations. An important development in type of craft to meet these requirements is the SWATH (small waterplane area twin hulled) ship. The SWATH ship's capabilities are achieved by placing the greater portion of the ship's buoyant volume below the sea surface and supporting the above-surface structure by thin struts which are little affected by wave action. Stability is exceptional both underway and at rest in sea states up to 7. The concept includes full automatic control over pitch, heave, roll, yaw, and sway. The 190-ton Stable Semisubmerged Platform (SSP KAIMALINO, figure 14) was designed and developed at NOSC to satisfy a need for a small, oceangoing work platform which would have the reduced motion, greater deck space, and higher speed of much larger conventional monohulls. The SSP measures 89 feet (27 meters) in length and 45 feet (14 meters) in width. The vessel was designed by NOSC with support from the Pearl Harbor Naval Shipyard; it was constructed at the Coast Guard Yard at Curtis Bay, Maryland.

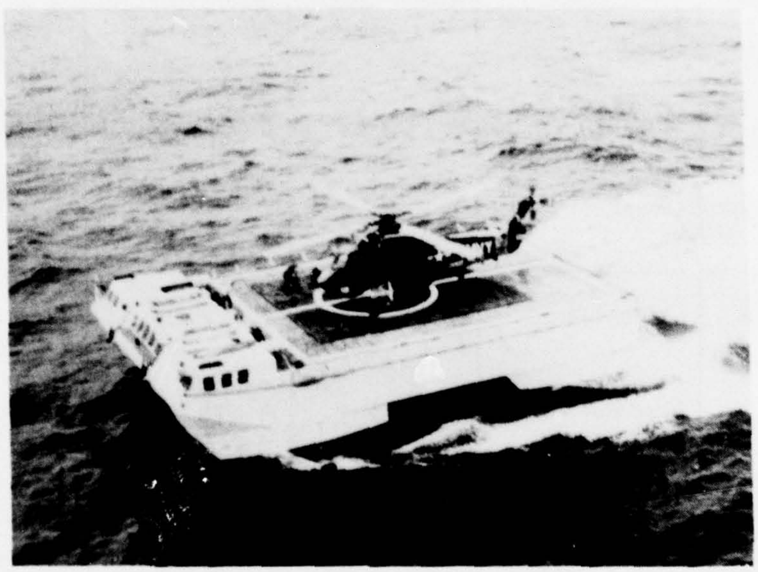

Figure 14. SSP KAIMALINO, a SWATH ship.

The SSP has two submerged, parallel, torpedo-like hulls which support a cross-structure above water by means of four streamlined, vertical, surface-piercing struts. Two controllable canard fins are located near the hull bows, and a full-span stabilizing fin with controllable flaps is near the hull stern. The fins provide dynamic stability, damping, and control over heave, pitch, and roll. The design configuration of the SSP will permit normal operations in 9-foot (3 meters) waves. With a full fuel complement of 18.8 tons, the SSP

will have an operating range of approximately 350 nautical miles at a cruise speed of 24 knots (12 meters per second). Two T64-GE-6B turboshaft engines of approximately 2000 horsepower each are used to drive 78-inch-diameter (198 centimeters), controllable and reversible pitch propellers.

## SYSTEM SYNTHESIS

With all component parts defined and demonstrated for various tasks, we will use a recently completed, research-and-development task as a case history of the synthesis of a vehicle for a particular application. The task chosen for this example is the need for recovery of the solid rocket boosters (SRBs) used in the launch of the NASA space shuttle vehicle into space orbit. After burn-out of the SRBs during the initial trajectory of the shuttle, the 12-foot-diameter (4 meters) by 140-foot-long (43 meters) SRBs are jettisoned and dropped into the sea by parachutes. Upon sea impact they float upright in a "spar" mode with the nozzle opening down. The task was to provide a means to descend to the depth of the rocket nozzle 100 feet (31 meters) and insert a plug so that the residual water could be removed and the SRB tilted to a "log" mode for towing to a reclamation site for reuse.

The SRB dewatering system consists of a nozzle plug, control console, power distribution subsystem, and umbilical cables. The remotely controlled, undersea vehicle portion of this system, designated nozzle plug (NP), is 14 feet high (4 meters), from 2.5 to 7.0 feet in diameter (0.8 to 2 meters), and weighs 3300 pounds (1500 kilograms) in air (figure 15). The NP was designed with a modular approach for ease of fabrication and maintenance. The six modules can be described as follows:

HYDRAULIC MODULE - The hydraulic module houses two, 15-horsepower, electro-hydraulic pumps. These units provide the power to the four vertical and two horizontal thrusters and the locking arms. The hydraulic system operates at 3000 pounds per square inch (21 megapascals).

TRANSITION MODULE - The transition module provides the transfer interface for all pneumatic, electrical, and hydraulic functions. It is the structural portion of the NP and has the thrusters and shock-mitigating bumpers mounted on it. The bumpers provide the means to seat the NP in the nozzle of the SRB prior to the deployment of the locking arms. Each bumper has a proximity switch and provides a signal displayed as a light on the control console as the NP becomes firmly seated in the SRB nozzle. The framework provides the conduit for the electrical power and the air supply from the ship.

ELECTRICAL MODULE - The electrical module houses all NP control functions, e.g., signal control relays, thruster controls, and sensors.

INFLATABLE BAG MANDREL MODULE - The inflatable bag mandrel module holds the inflatable bag used to seal the nozzle of the SRB during second-stage dewatering (log mode). The bag is designed to inflate from 30 inches (76 centimeters) in diameter to 56 inches (142 centimeters) in diameter to seal the nozzle. The design is based upon the Goodrich space saver tire concept. The mandrel also houses the dewatering pipe and syntactic foam for flotation.

LOCKING ARM MODULE - The locking arm module provides the NP with the means to secure itself firmly to the nozzle once docking has been assured. The locking arms are deployed by individual piston-cylinder arrangements. An over-center design

is used to insure locking in the event of hydraulic failure. Syntactic foam is fitted around this section to provide buoyancy.

DEWATERING MODULE - The dewatering module contains the dewatering hose, television camera and lights, and search-and-recovery system (SAR). Buoyancy is also provided through syntactic foam. The dewatering hose is used to channel the water out of the SRB when the log mode has been attained. The hose is wire-helixed rubber stowed in the central cylinder of the module. A spring-loaded arrangement is used to deploy the hose. The television camera is mounted to provide video displays on the monitor. The lights have half-power and full-power operational capabilities. SAR equipment includes an acoustic pinger, strobe light, and lifting eyes.

The nozzle plug is launched from a support ship and is maneuvered on the surface to the SRB. The plug is then submerged and performs an inspection of the SRB casing, utilizing the television camera system. The operator then acquires the nozzle opening by using the same television system. The plug is positioned beneath the SRB, using the horizontal and vertical thrusters, and at the appropriate time is driven up into the nozzle's throat. Upon docking, indicator lights on the console show that the plug is seated and that the locking arms are deployed to hold the nozzle plug in position. Dewatering air is activated through the umbilical cable and a pressure differential is attained, thus forcing out the water. As the water is egressed, the SRB raises out of the water, becomes unstable, and falls over into a log mode. At this time, the sealing bag is inflated on the plug to prevent air loss. Dewatering continues until the SRB is emptied. The umbilical cables are disconnected from the ship and the SRB is towed to port. At port, the nozzle plug is removed as the seal and refurbishment of the SRB is begun.

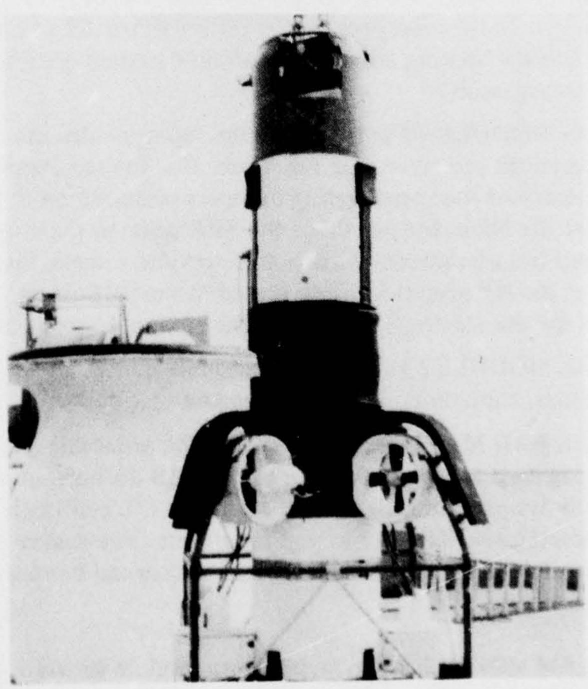

Figure 15. SRB nozzle plug.

## CONCLUSION

To develop work systems that effectively operate in the undersea environment there must be a close coupling of the definition of the tasks to be performed and an understanding of the undersea environment. The vehicles, sensors, tools, and support equipment must be carefully integrated to match the human operator's capabilities. Optimizing one component of a system, or overly sophisticating another component to meet all possible requirements, can work to the detriment of the total system, and a balance in requirements, particularly including the human operator, is necessary.

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